The Physics of Signal Propagation in a Cellular Environment

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Objective

- To illustrate that an electromagnetic macro modeling can properly predict the path loss exponent in a mobile cellular wireless communication system.
- **Path loss exponent in a cellular wireless communication system is 3, preceded by a slow fading region, and followed by the fringe region where the path loss exponent is 4.**
- **Experiments: Okumura et al. and more extensive experimental data from different base stations.**

Dennis Gabor wrote:[1972, IEEE Trans on Information Theory, First Issue]

The wireless communication systems are due to the generation, reception and transmission of electro-magnetic signals. Therefore all wireless systems are subject to the general laws of radiation.

Communication theory has up to now been developed mainly along mathematical lines, taking for granted the physical significance of the quantities which are fundamental in its formalism.

But communication is the transmission of physical effects from one system to another. Hence communication theory should be considered as a branch of physics.

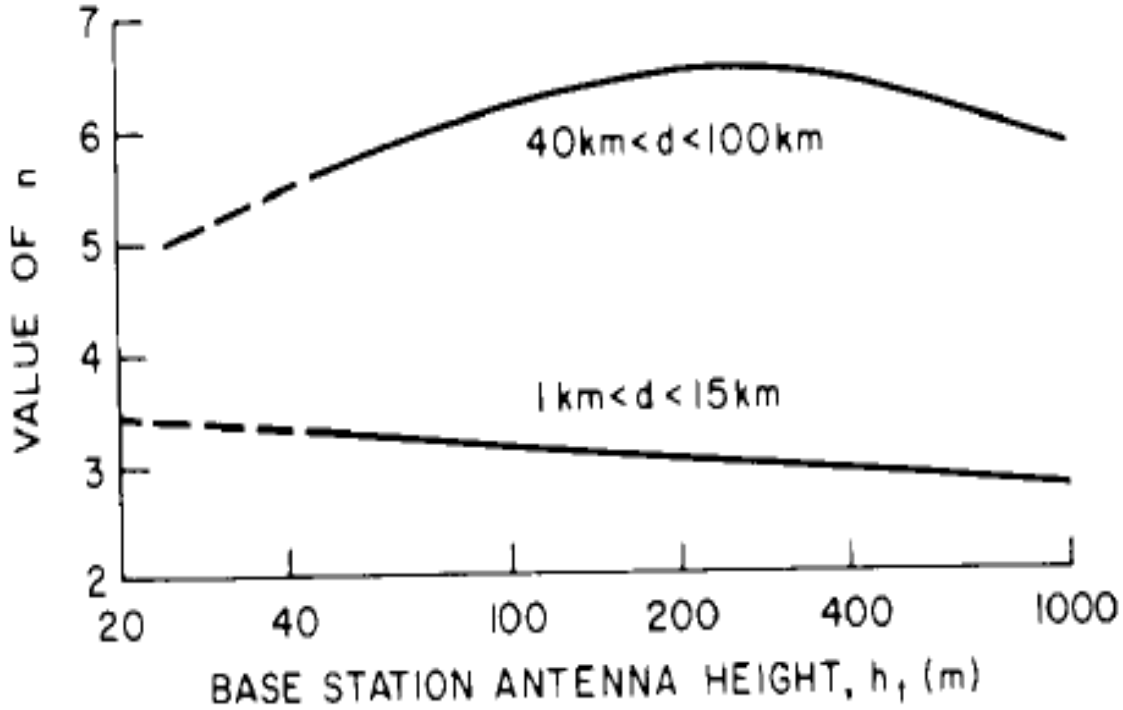
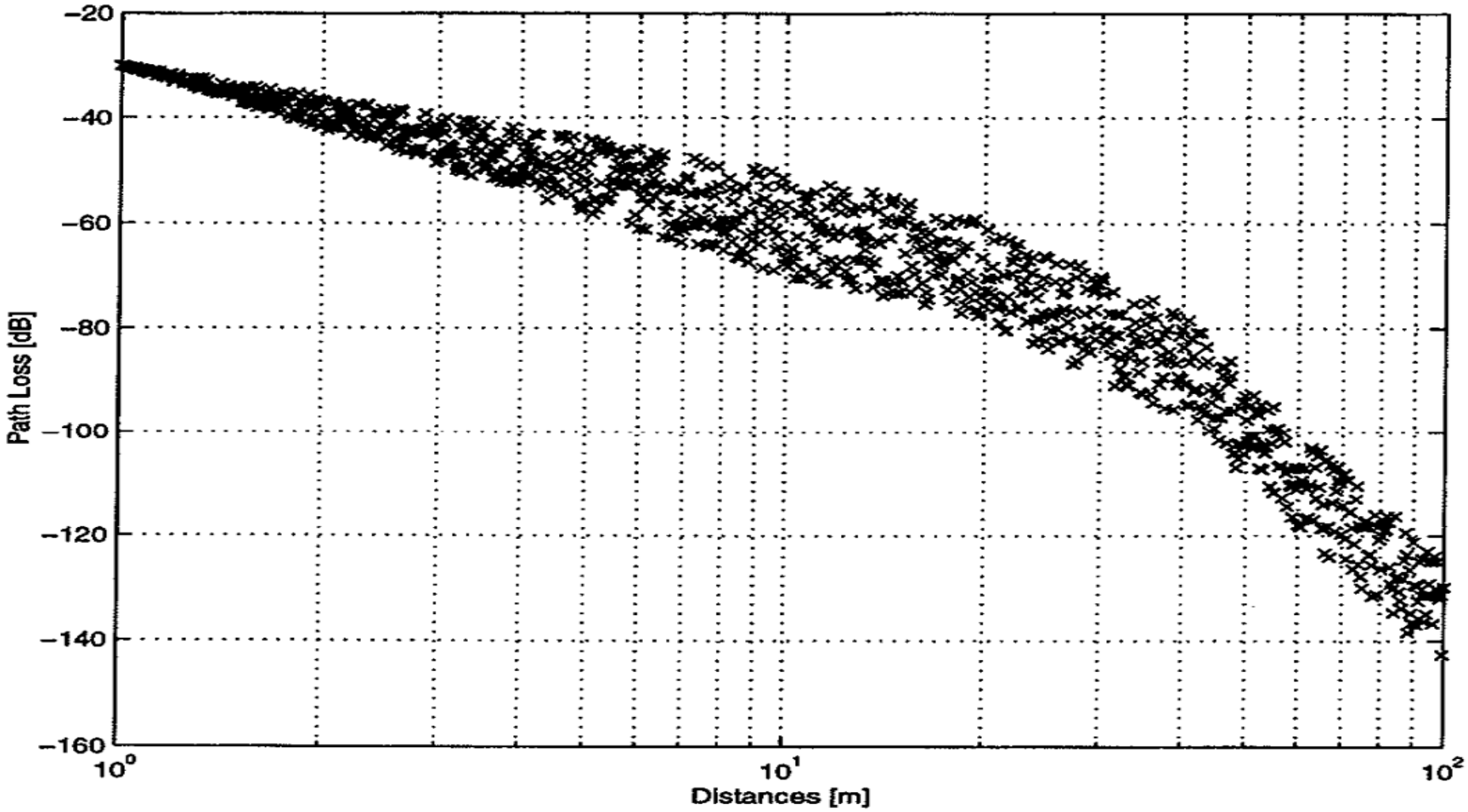


Figure 2.2-14 Distance dependence of median field strength in an urban area ($P_r \alpha d^{-n}$).



Prediction from Ericsson in-building path loss model. Reproduced by permission from Simon R. Saunders, Advances in mobile propagation prediction methods, Chapter 3 of *Mobile Antenna Systems Handbook,* Edited by: Kyohei Fujimoto, Artech House, 2008.

This is one of the earliest experiments which aimed to check the existence of Sommerfeld surface waves

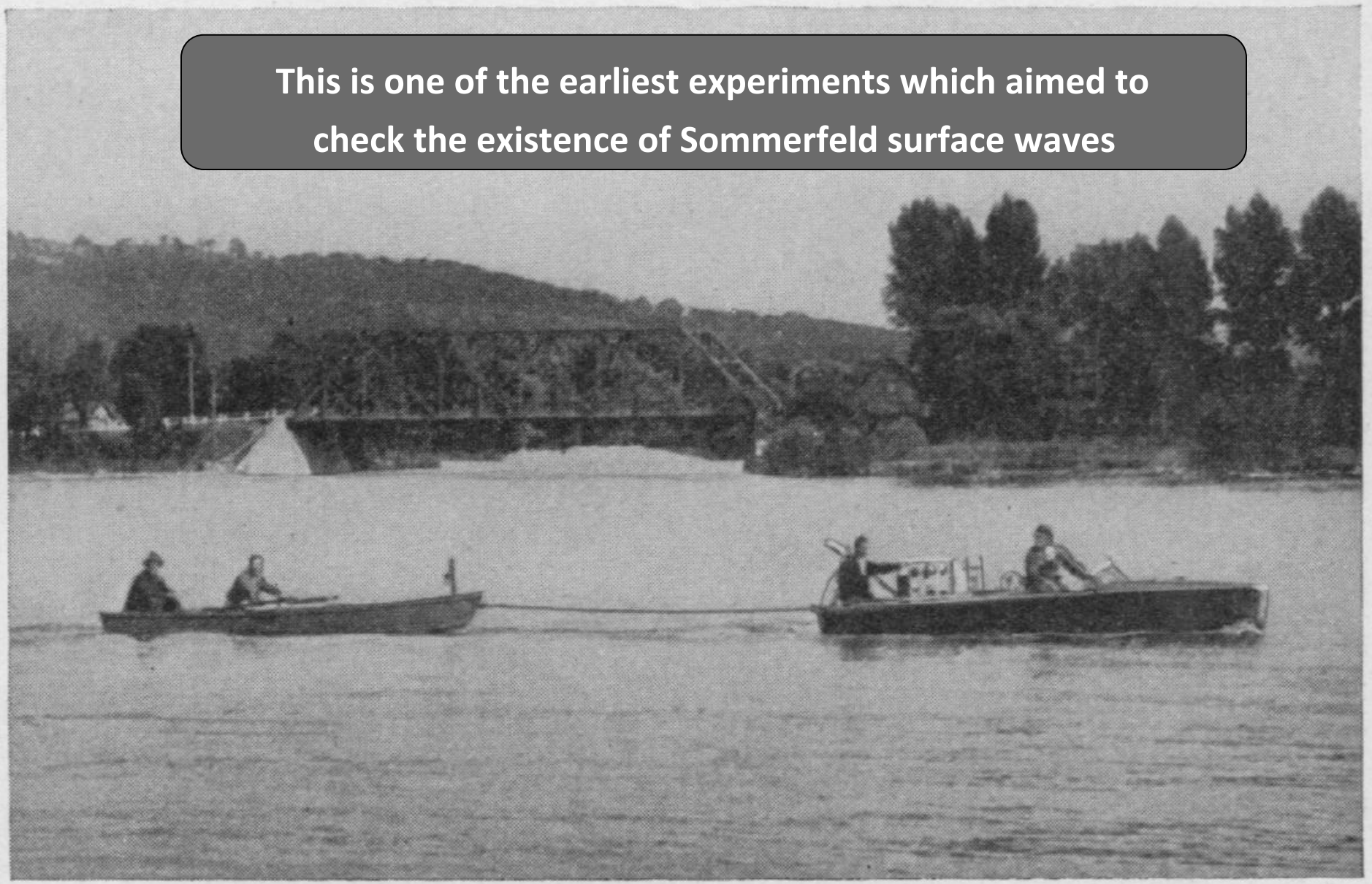


Fig. 1—Experimental arrangement for determining the variation of the received field strength with distance.

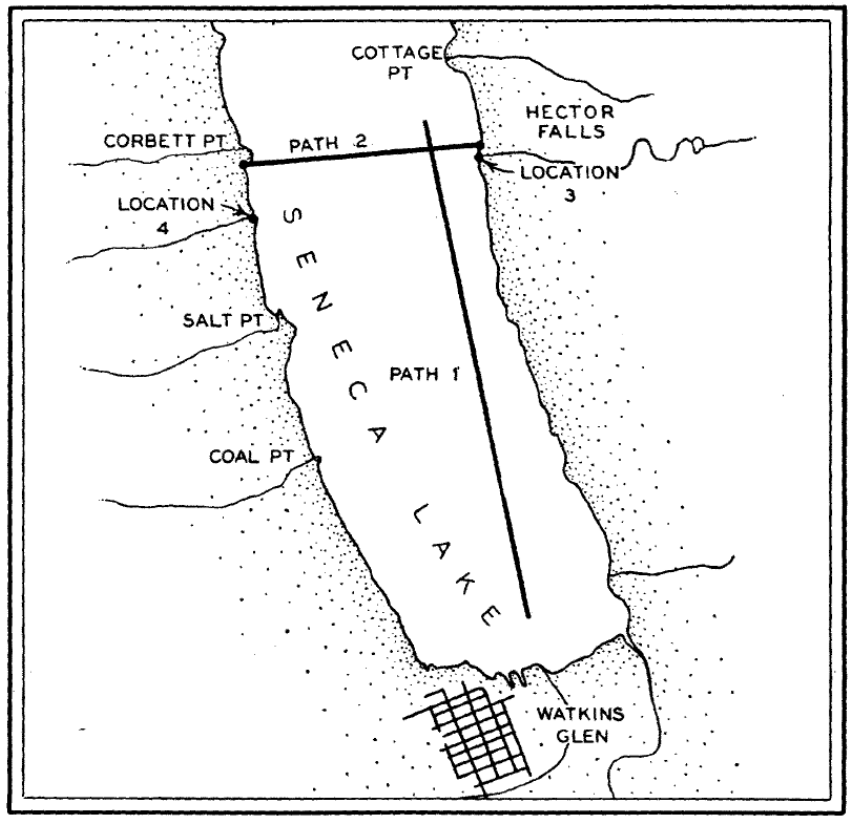
Proceedings of the Institute of Radio Engineers
Volume 25, Number 2 *February, 1937*

THE SURFACE WAVE IN RADIO PROPAGATION OVER PLANE EARTH*

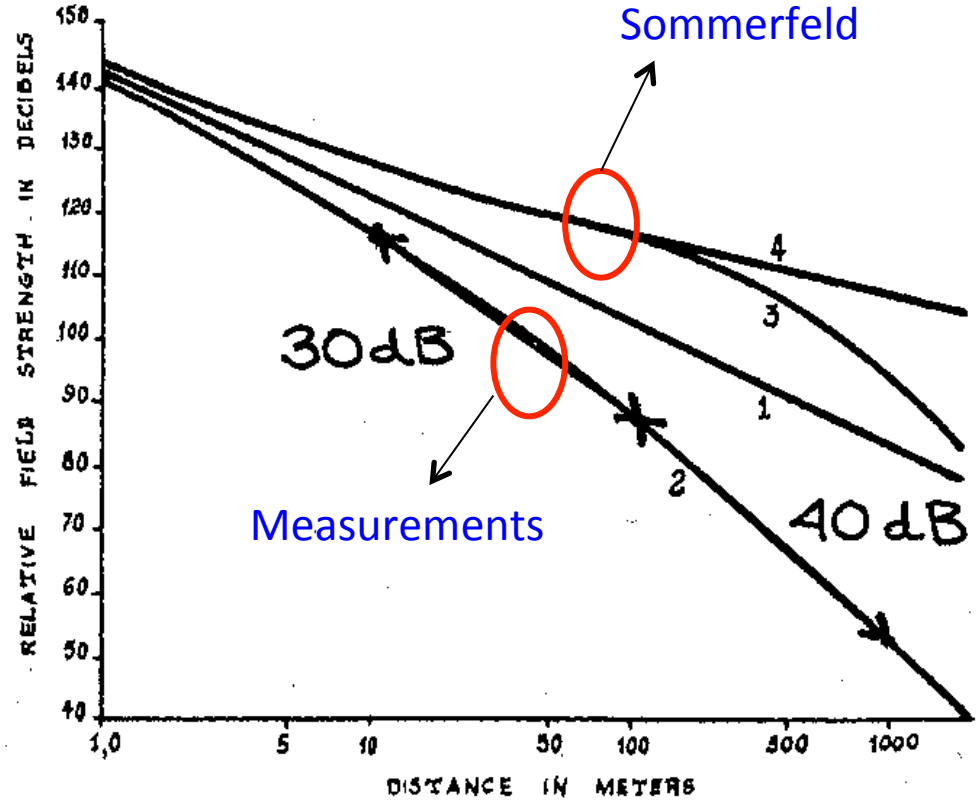
By

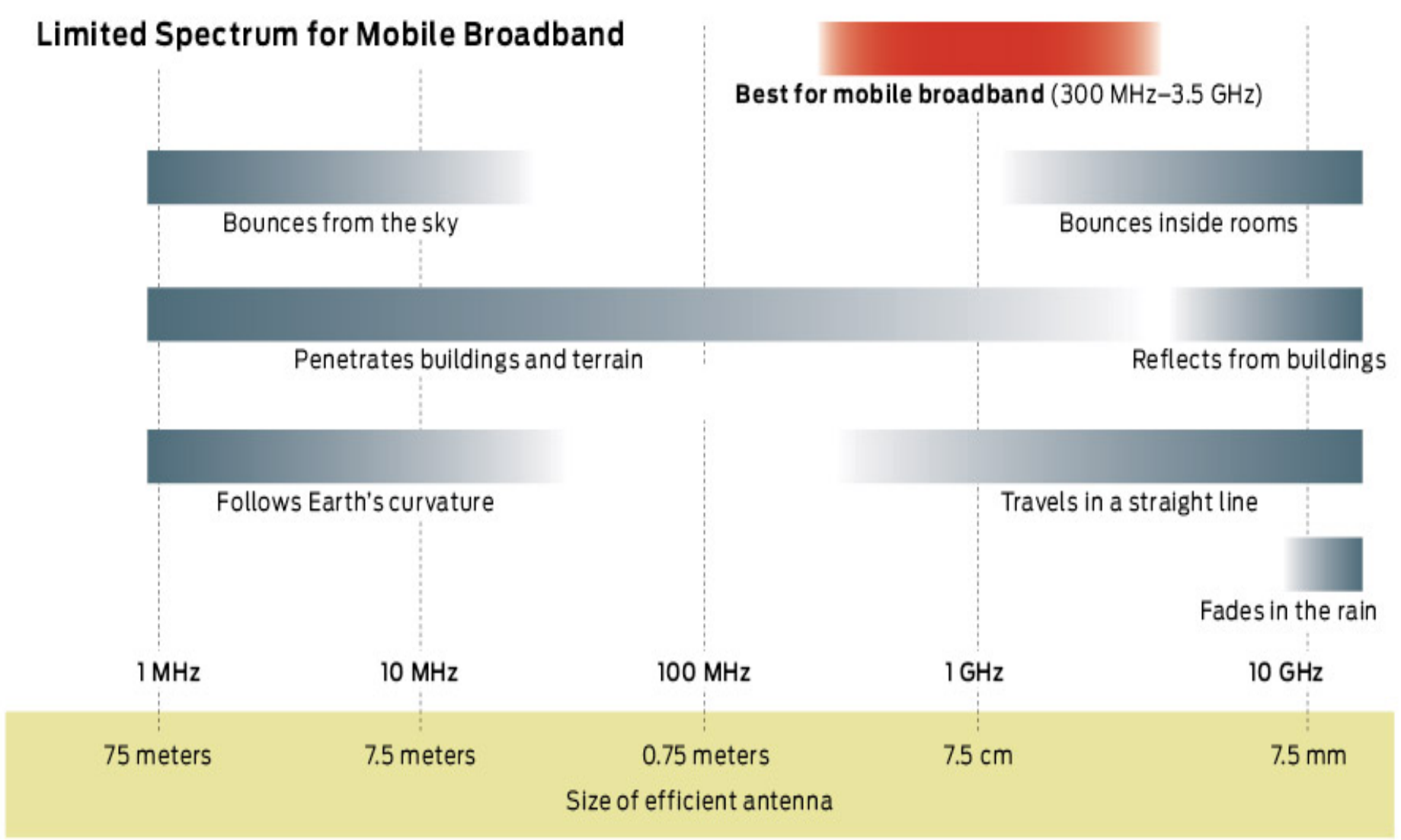
Charles R. Burrows

(Bell Telephone Laboratories, Inc., Deal, New Jersey)



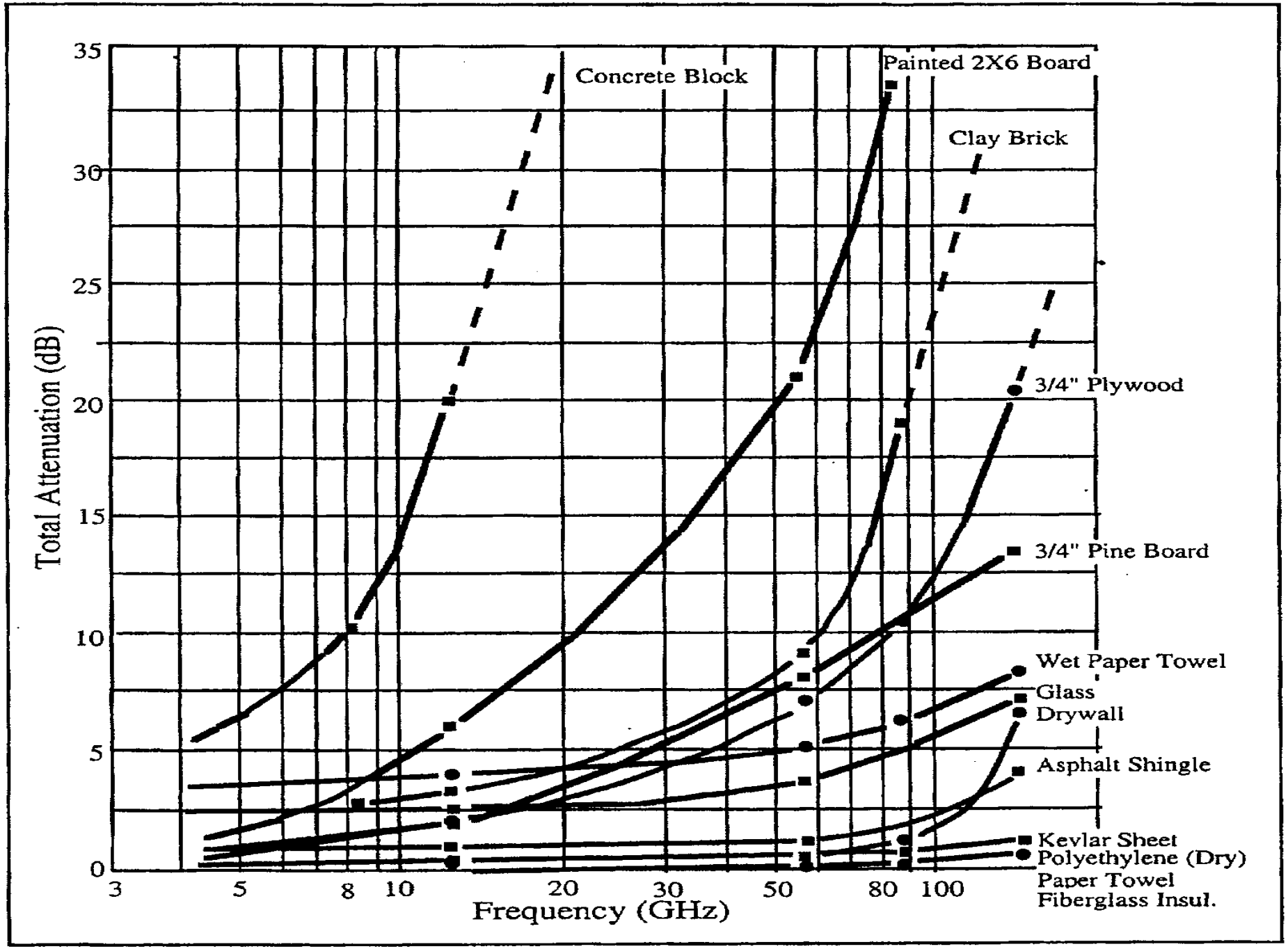
Analytical Solution by Sommerfeld





OPPORTUNITY WINDOW: The best frequencies for mobile broadband are high enough that the antenna can be made conveniently compact, yet not so high that signals will fail to penetrate buildings. This leaves a relatively narrow range of frequencies available for use [red band].

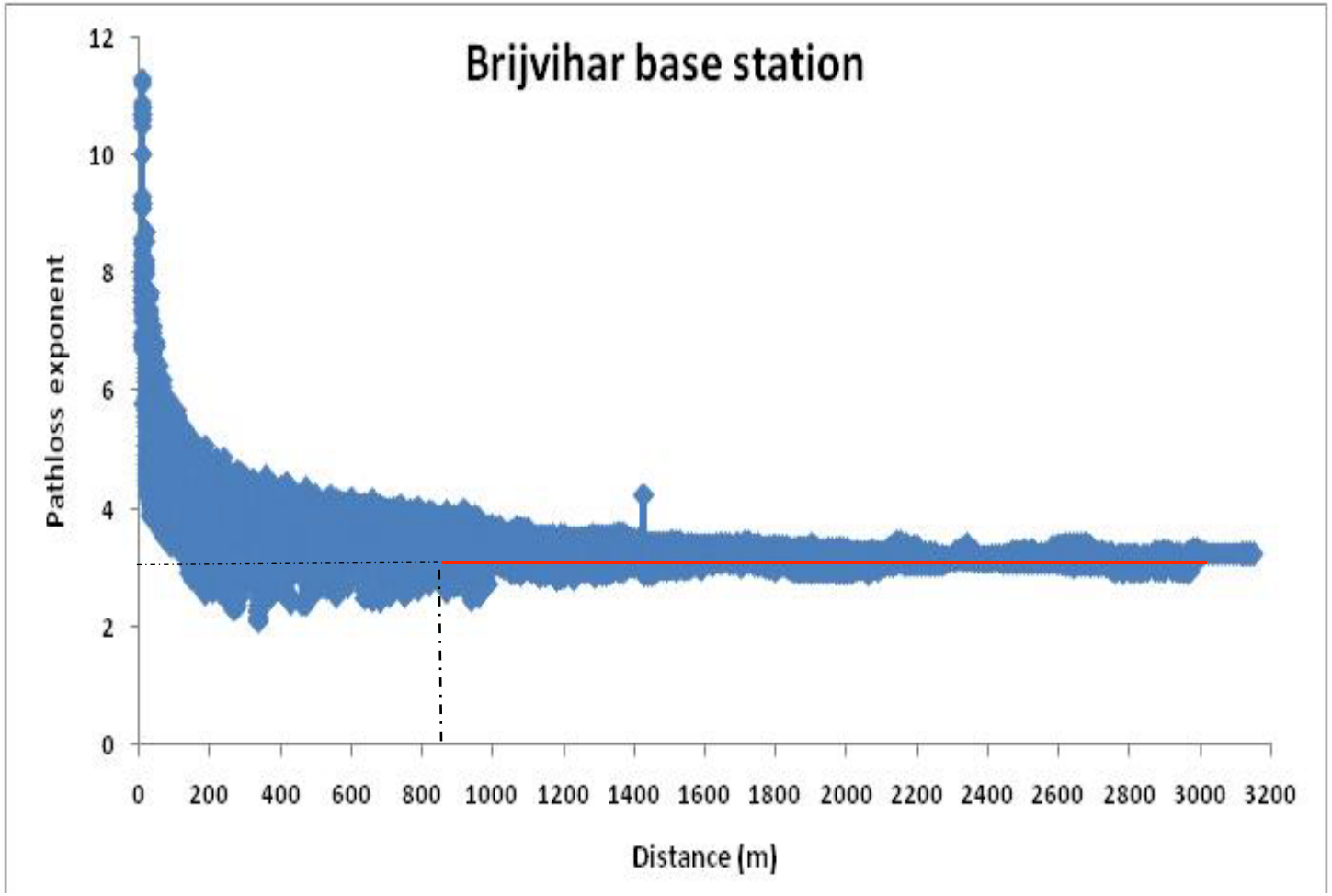
IEEE SPECTRUM Magazine, October 2010, pp. 29


Concrete Block
Painted 2X6 Board
Clay Brick
3/4" Plywood
3/4" Pine Board
Wet Paper Towel
Glass
Drywall
Asphalt Shingle
Kevlar Sheet
Polyethylene (Dry)
Paper Towel
Fiberglass Insul.
Total Attenuation (dB)
Frequency (GHz)
0
5
10
15
20
25
30
35
3
5
8
10
20
30
50
80
100

Experimental Data

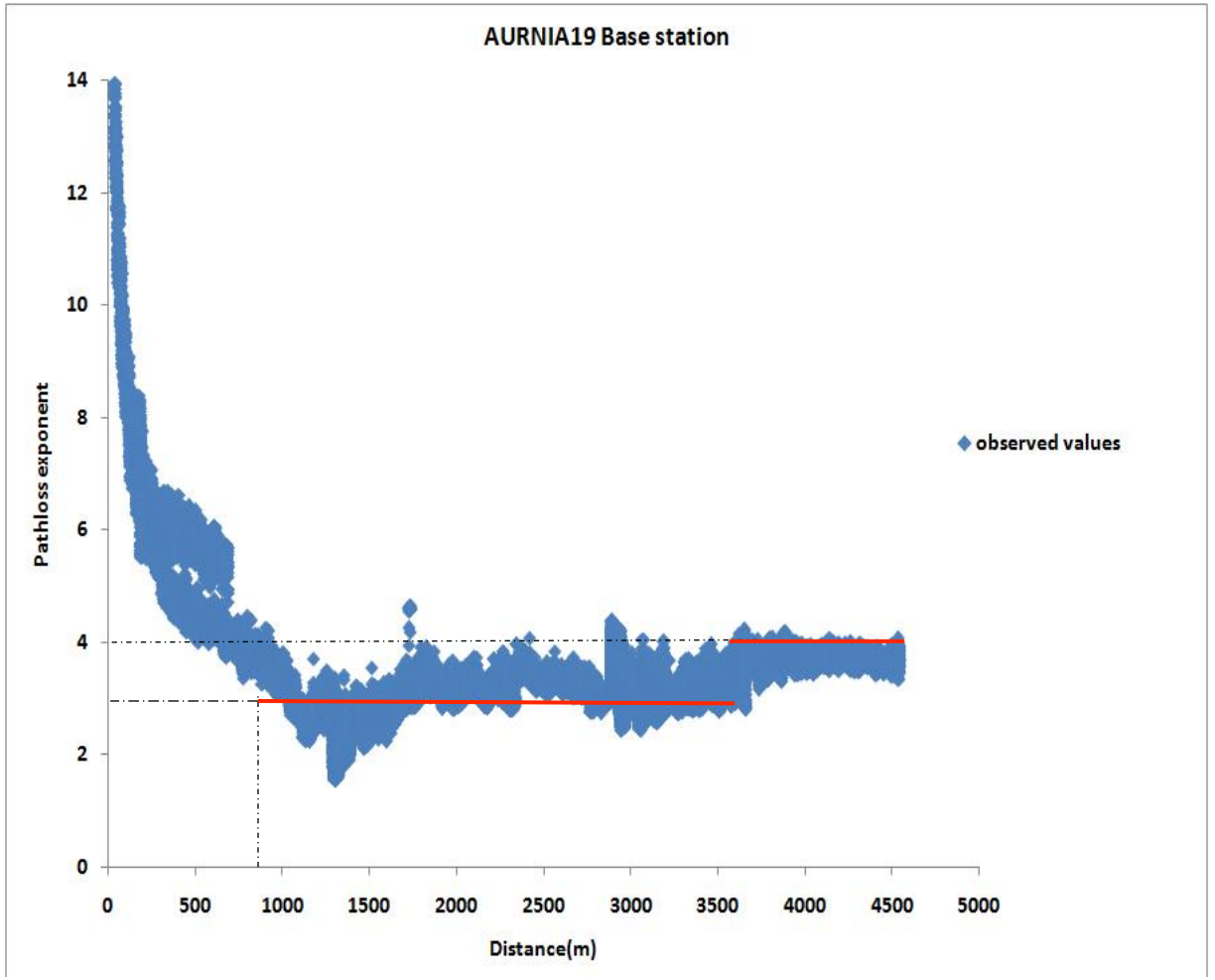
Photograph of a Delhi typical urban environment in this study.

Experimental Data



Variation of path loss exponent with distance for BJV base station (1800 MHz). Base station height: 24 m. Beginning of smooth region: 864 m.

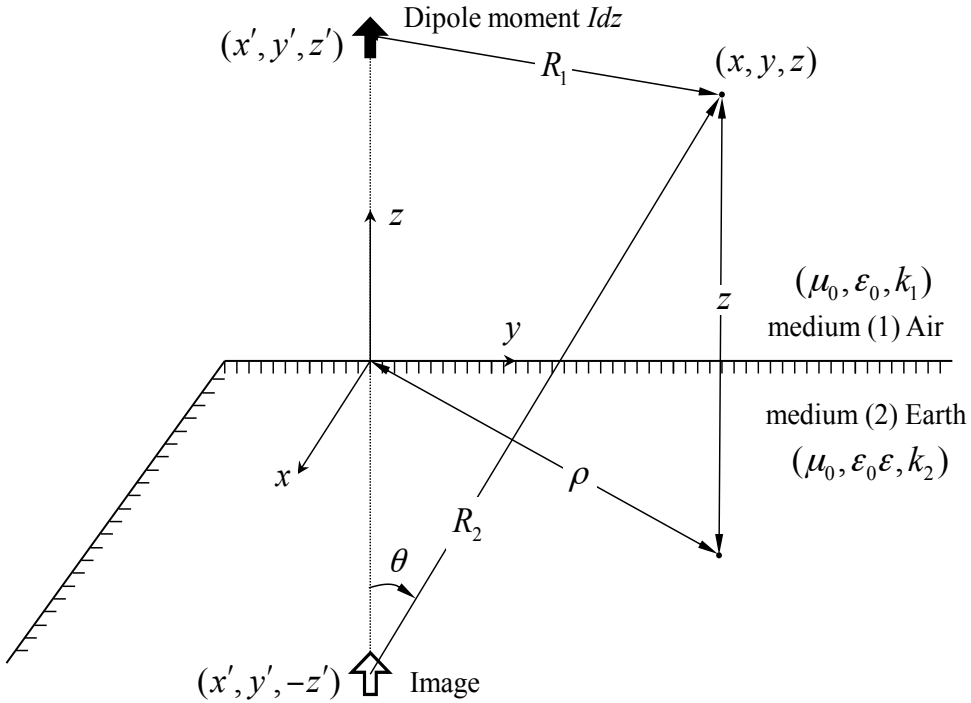
Experimental Data



Variation of path loss exponent with distance for AURNIA 19 base station (900 MHz). Base station height: 50 m. Beginning of smooth region: 900 m.

Theory – Sommerfeld Formulation

- Dipole of moment *Idz* oriented along the *z*-direction and located at (*x*', *y*', *z*') over an imperfect ground plane of complex relative dielectric constant ε.



$$k_1^2 = \omega^2 \mu_0 \varepsilon_0$$

$$\varepsilon = \varepsilon_r - \frac{j\sigma}{\omega \varepsilon_0}$$

$$k_2^2 = \omega^2 \mu_0 \varepsilon_0 \varepsilon$$

Theory – Sommerfeld Formulation

- Solution:

$$\Pi_{1z} = P\left[\left[\frac{\exp(-jk_1R_1)}{R_1} + \int_0^\infty \frac{J_0(\lambda\rho)}{\sqrt{\lambda^2 - k_1^2}} \frac{\varepsilon\sqrt{\lambda^2 - k_1^2} - \sqrt{\lambda^2 - k_2^2}}{\varepsilon\sqrt{\lambda^2 - k_1^2} + \sqrt{\lambda^2 - k_2^2}} \exp\left(-\sqrt{\lambda^2 - k_1^2}\,(z+z')\right)\lambda\, d\lambda\right]\right]$$

$$\Pi_{2z} = 2P\int_0^\infty \frac{J_0(\lambda\rho)\exp\left(\sqrt{\lambda^2 - k_2^2}\,z - \sqrt{\lambda^2 - k_1^2}\,z'\right)}{\varepsilon\sqrt{\lambda^2 - k_1^2} + \sqrt{\lambda^2 - k_2^2}}\lambda\, d\lambda$$

for $Real\left[\sqrt{\lambda^2 - k_{1,2}^2}\right] > 0$, where

$$P = \frac{I\, dz}{j\omega 4\pi\varepsilon_0} \qquad \rho = \sqrt{(x-x')^2 + (y-y')^2} \qquad R_1 = \sqrt{\rho^2 + (z-z')^2}$$

Theory – Field Near the Interface

- For $|\varepsilon| \to \infty \quad \theta \approx \pi/2$, and ***W* small**,

$$G_{sV} \approx -\sqrt{\frac{2\pi k_1 j}{R_2}}\exp\left[-jk_1R_2\right]\frac{(z+z')}{R_2}\frac{\varepsilon}{\sqrt{\varepsilon^2-1}} \approx -\sqrt{2\pi k_1 j}\,\frac{(z+z')\exp\left[-jk_1R_2\right]}{R_2^{1.5}}$$

and three facts can be recognized:

- A variation of the Hertz potential as $\Pi_{1z} \propto \frac{1}{R_2^{1.5}}$ which will give a field variation of $\frac{1}{\rho^{1.5}}$ if $z+z' \ll \rho$, or equivalently, a path loss exponent of 3.
- A height gain effect: see the $(z+z')$ term.
- **No dependence with the ground parameters.**

Theory – Field Near the Interface

- For $|\varepsilon| \to \infty$, $\theta \approx \pi/2$, and ***W* large**,

$$G_{sV} \approx 2\sqrt{\varepsilon}\exp\left[-jk_1R_2\right]\frac{\left(z+z'\right)}{R_2^2}\left[1-\frac{\varepsilon}{jk_1R_2}\right]$$

and four facts can be recognized:

  - A term with a variation of the Hertz potential as $1/R^2$, which is recognized as a **Norton surface wave**, and will give a path loss exponent of 4.
  - A higher order term with a variation as $1/R^3$.
  - A height gain effect for both terms.
  - **A dependence with the ground parameters for both terms**.

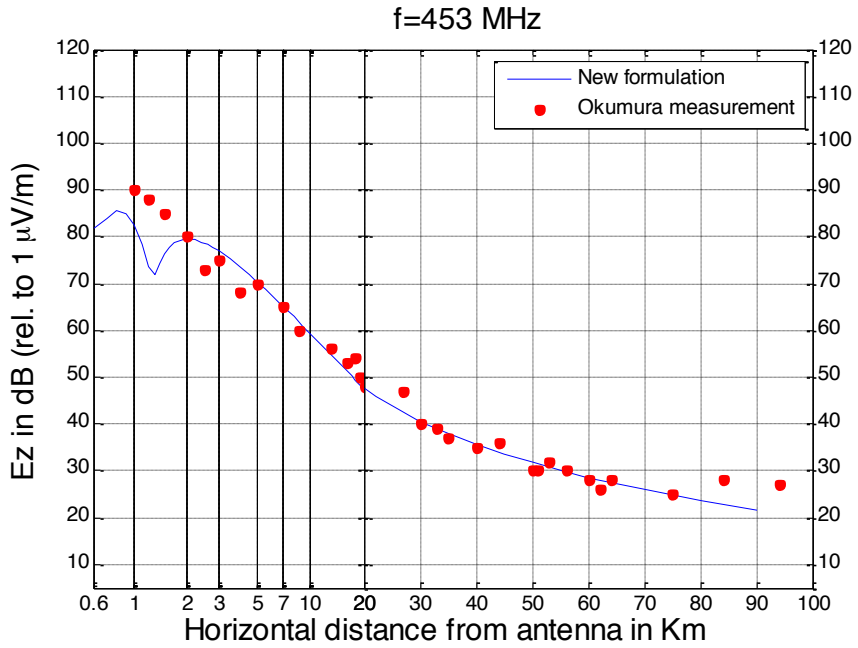
Theory – Field Near the Interface

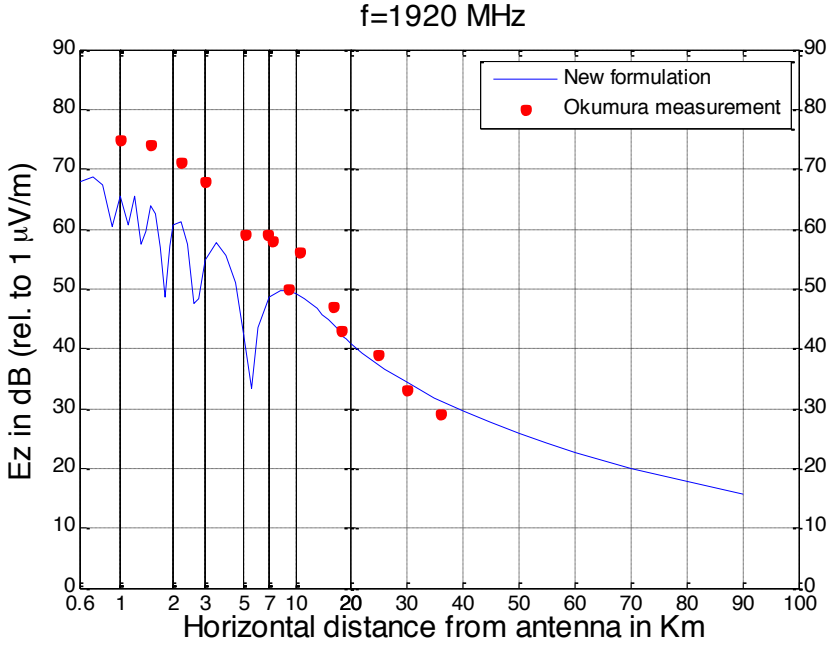
- In summary, the expressions for the total Hertz potential near the interface for $|\varepsilon| \to \infty$ and $\theta \approx \pi/2$ are:

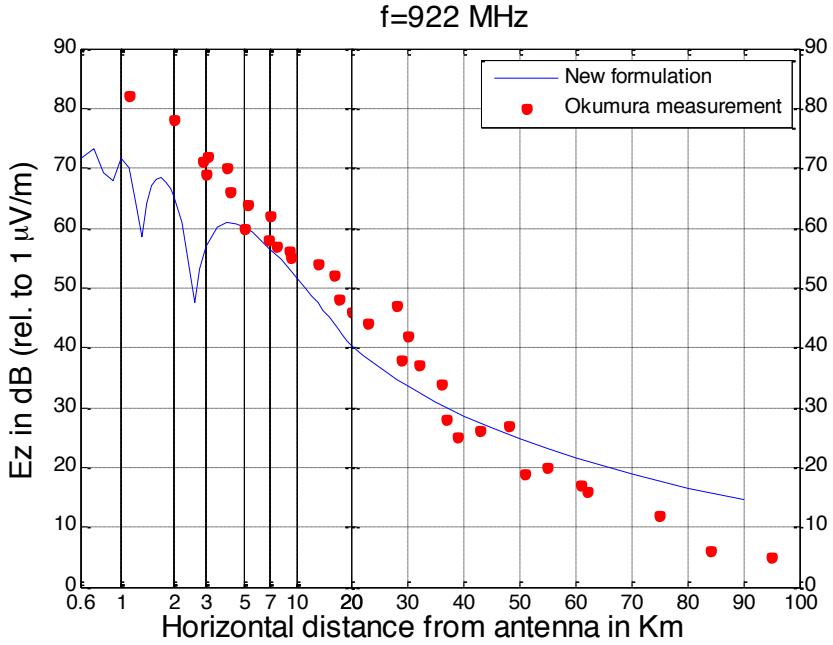
$$\Pi_{1z} \approx \begin{cases} P\left[\dfrac{\exp(-jk_1R_1)}{R_1} - \dfrac{\exp(-jk_1R_2)}{R_2} - \sqrt{j2\pi k_1}(z+z')\dfrac{\exp(-jk_1R_2)}{R_2^{1.5}}\right] & , W < 1 \\ P\left[\dfrac{\exp(-jk_1R_1)}{R_1} - \dfrac{\exp(-jk_1R_2)}{R_2} + 2\sqrt{\varepsilon}(z+z')\dfrac{\exp(-jk_1R_2)}{R_2^{2}}\left[1 - \dfrac{\varepsilon}{jk_1R_2}\right]\right] & , W > 1 \end{cases}$$

where we can recognize **two distinct regions**:

- the first one, closer to the dipole, with a path loss exponent of 3, height gain, and no dependence with the ground parameters;
- the second one, further away from the dipole, with a path loss exponent of 4, height gain and dependence with the ground parameters.

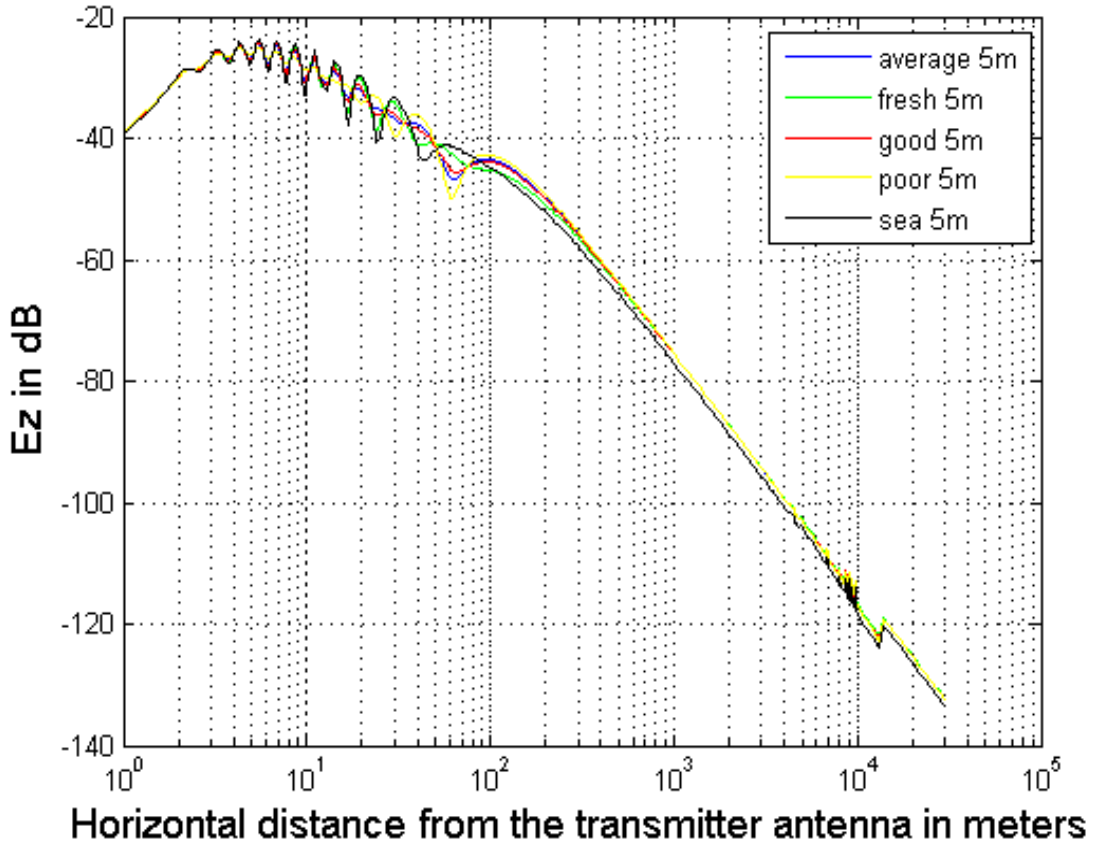






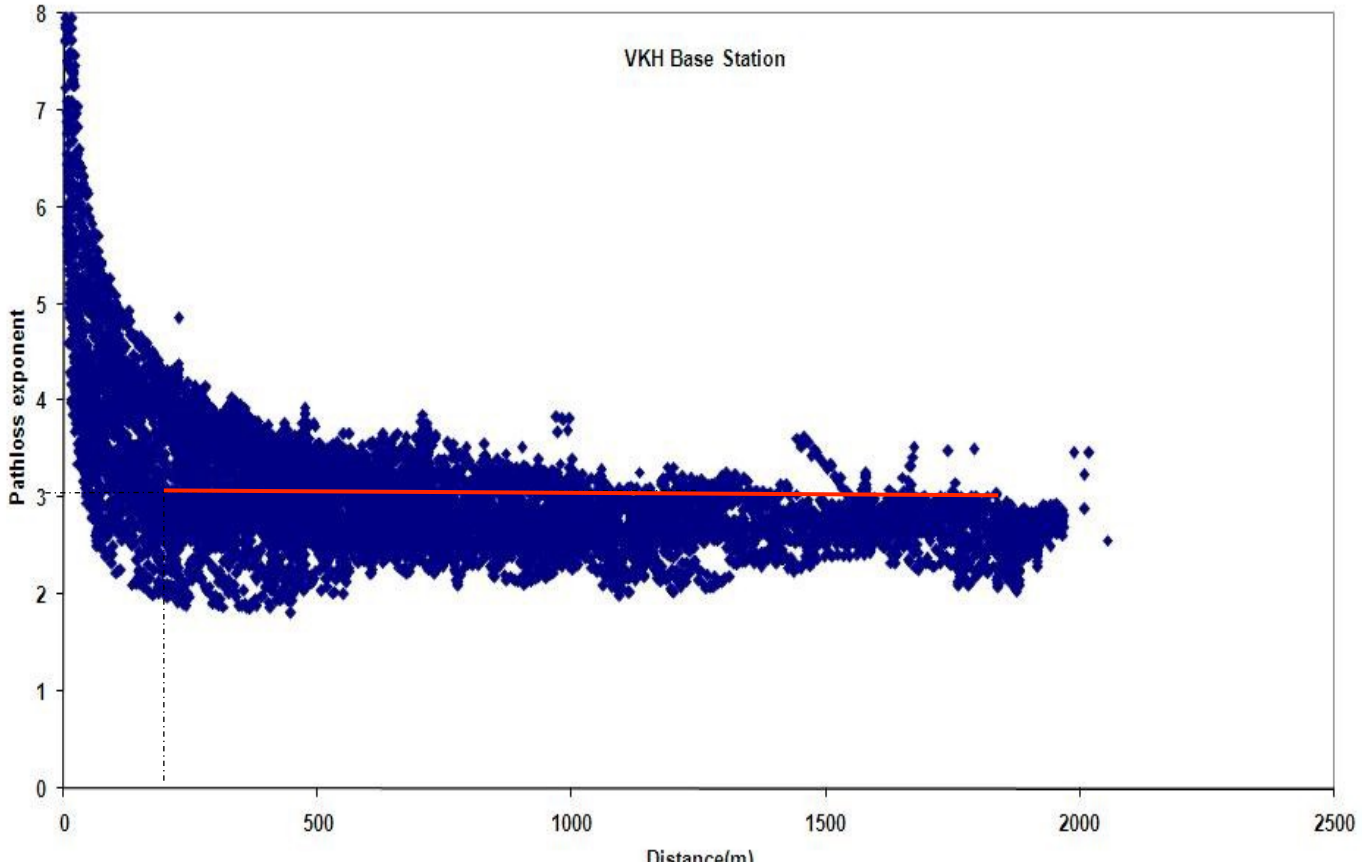
Comparison between Okumura's drive test measurements and the numerical analysis done using AWAS

Numerical Analysis – Field Near an Earth-Air Interface



Variation of magnitude of E_z from a half-wavelength dipole as a function of distance, at an operating frequency of 900 MHz. The height of the observation point was 2 m. Five different types of ground have been used, with different parameters.

Experimental Data



Variation of path loss exponent with distance for VKH base station (900 MHz). Base station height: 13 m. Beginning of smooth region: 234 m.

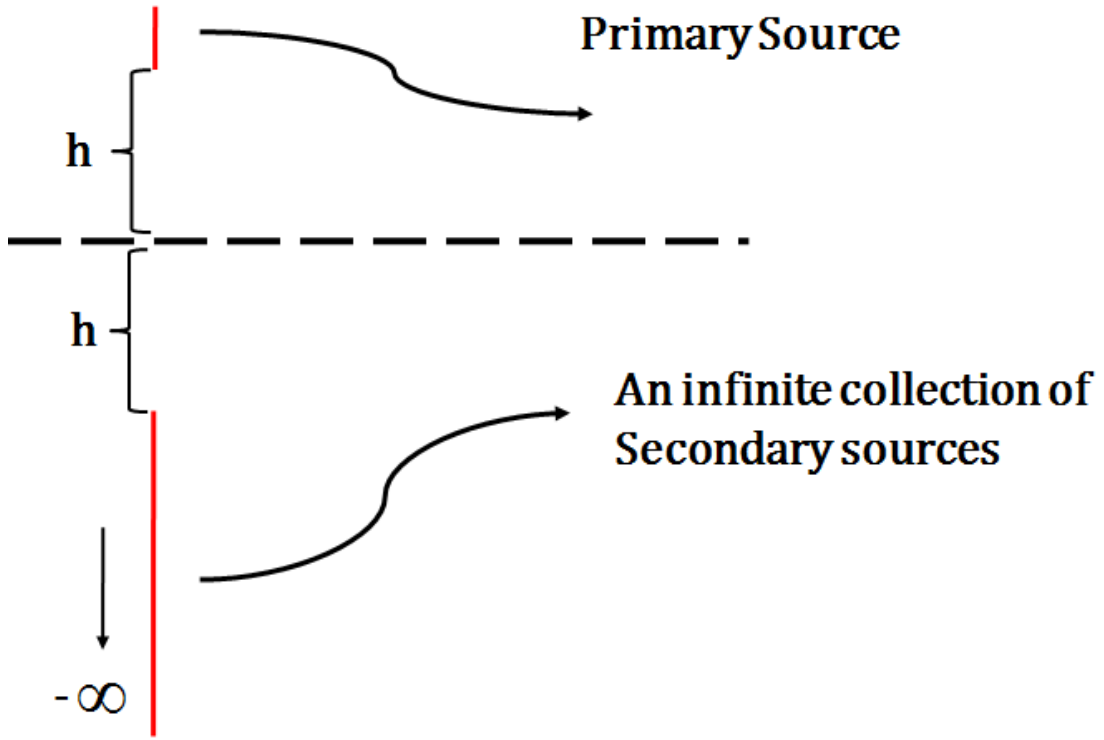
What Type of Wave Is It?

From the measurements shown it may be concluded:

- In all cases, most of the cell is in the near field region of the base station.
- Then, there is region with a path loss exponent of 3, i.e., with a decay of the field as $\frac{1}{\rho^{1.5}}$.
- Next, the region with a path loss exponent of 4, due to the Norton surface wave, follows
- The question arises: what type of wave is such that decays as $\frac{1}{\rho^{1.5}}$ in the intermediate region?

What Type of Wave Is It?

- Following Van der Pol and other researchers, it can be concluded that such wave is a surface wave originated by a 2D infinite source as the secondary sources shown in the following diagram which is precisely the situation in this problem



What Type of Wave Is It?

- An optical analog situation:

Range extension due to height gain

Surface wave continuous propagation after a big obstruction

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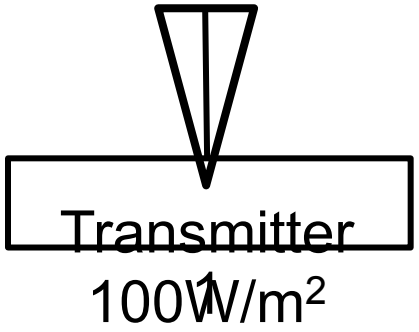
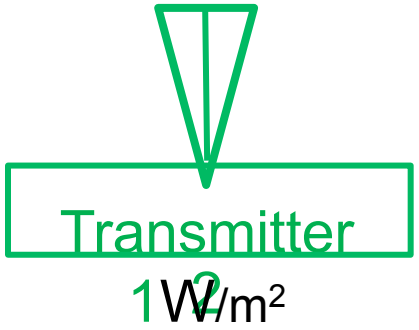
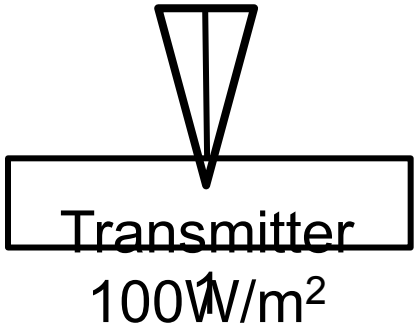
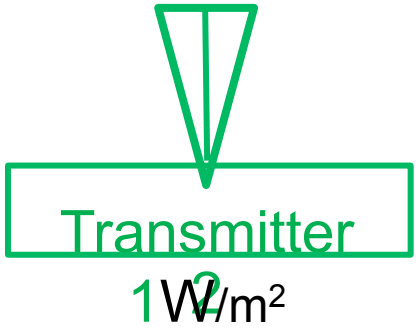




There will be constructive and destructive interference. So what will be the variation of power density in space?

(100 ± 1) W/m² ??





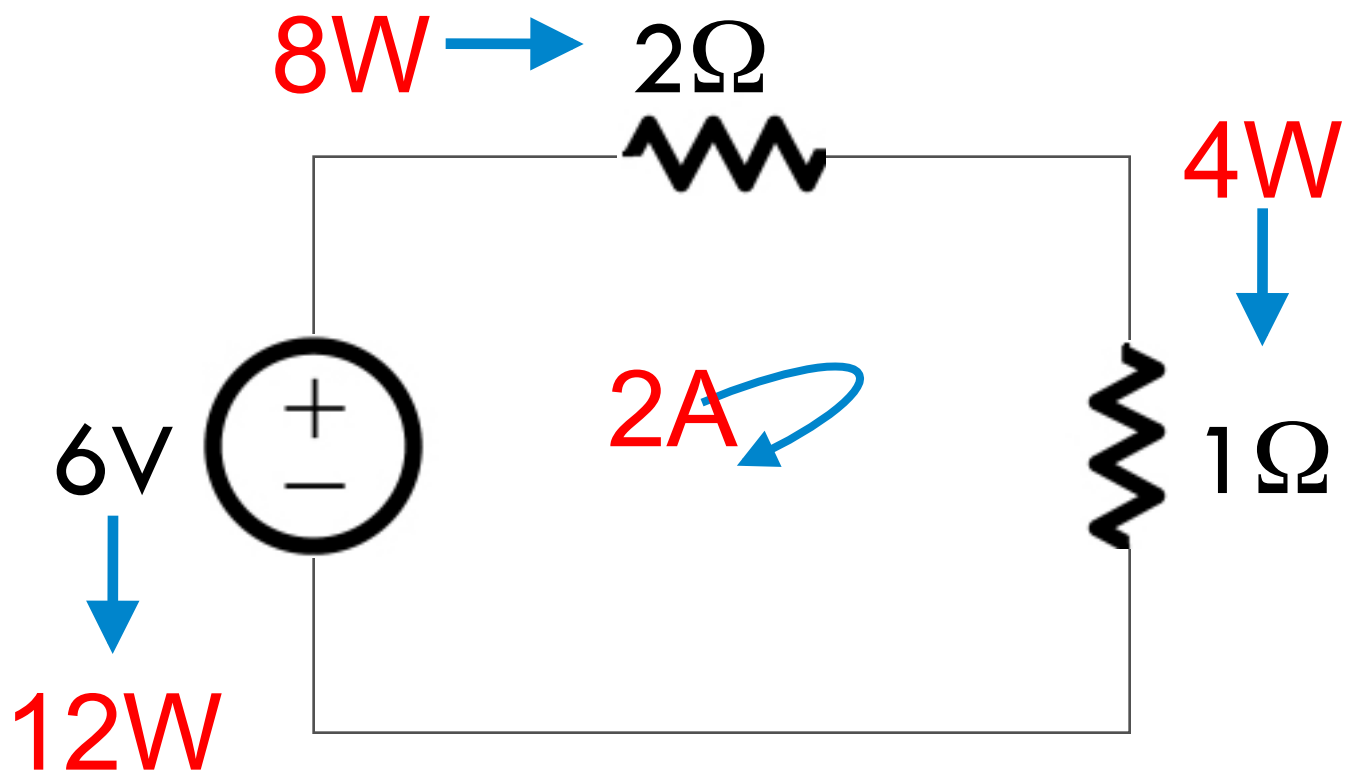
There will be constructive and destructive interference. So what will be the variation of power density in space?

(100 ±1) W/m² ??

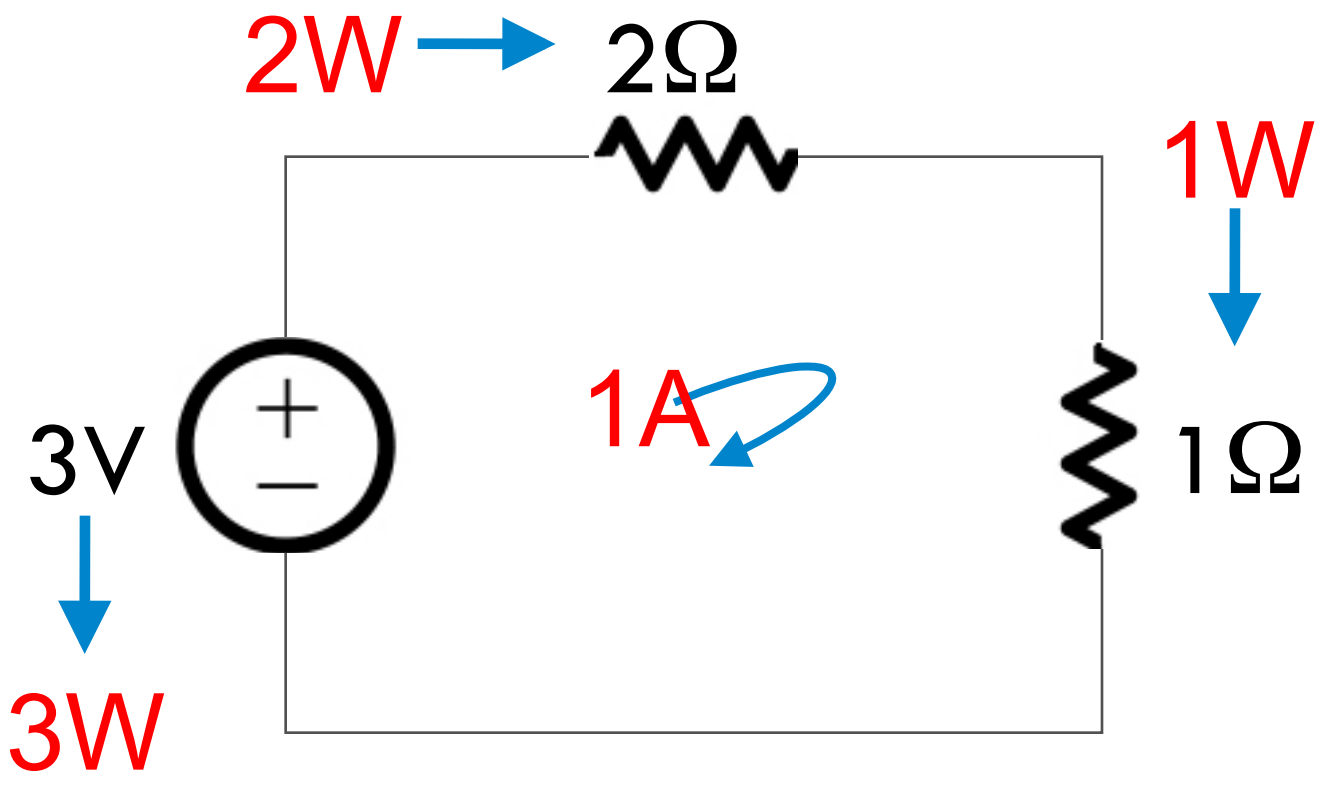
(121 ◄► 81) W/m²

A 40% variation even though the input power density variation is ONLY 1%!?

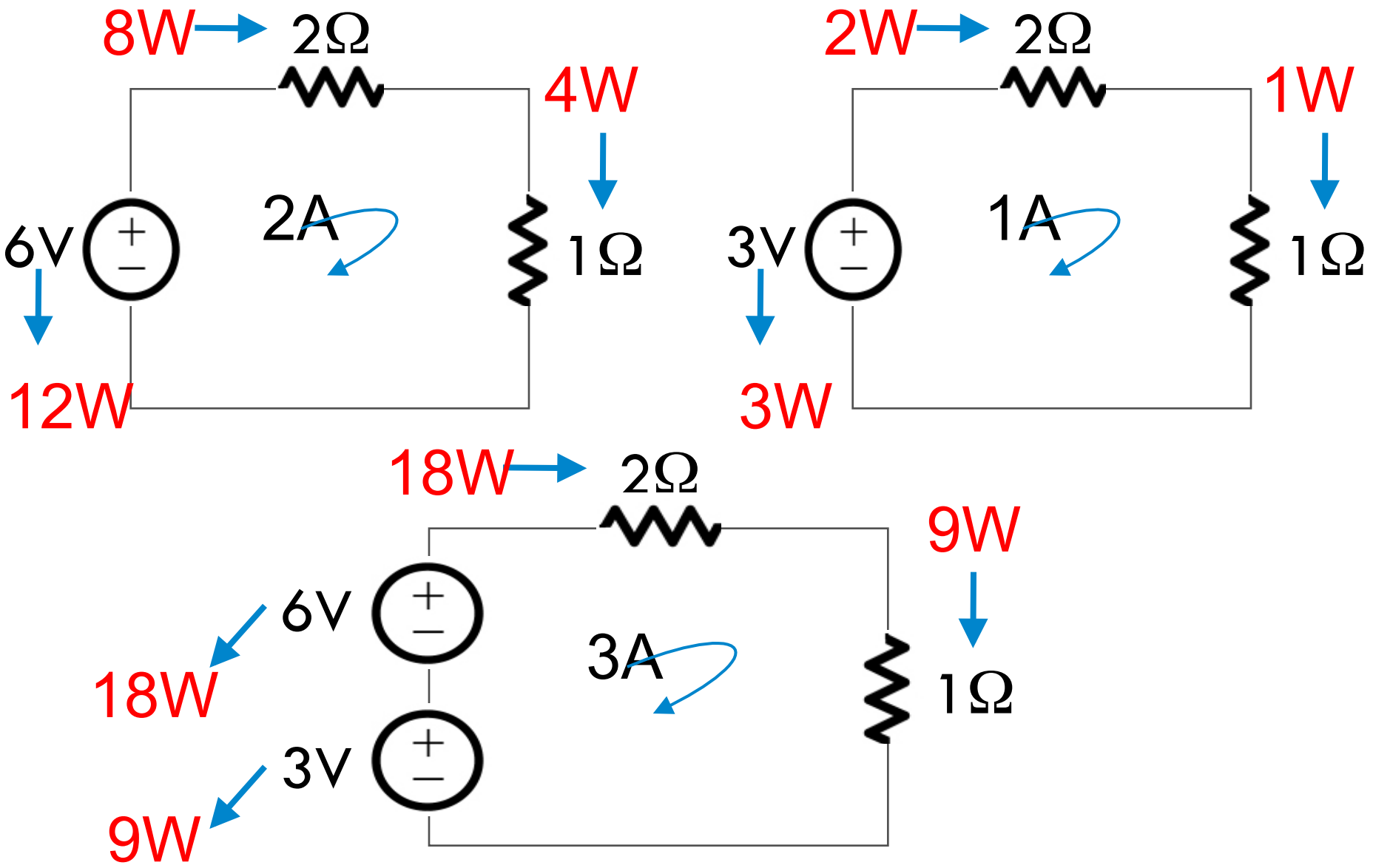
Case A



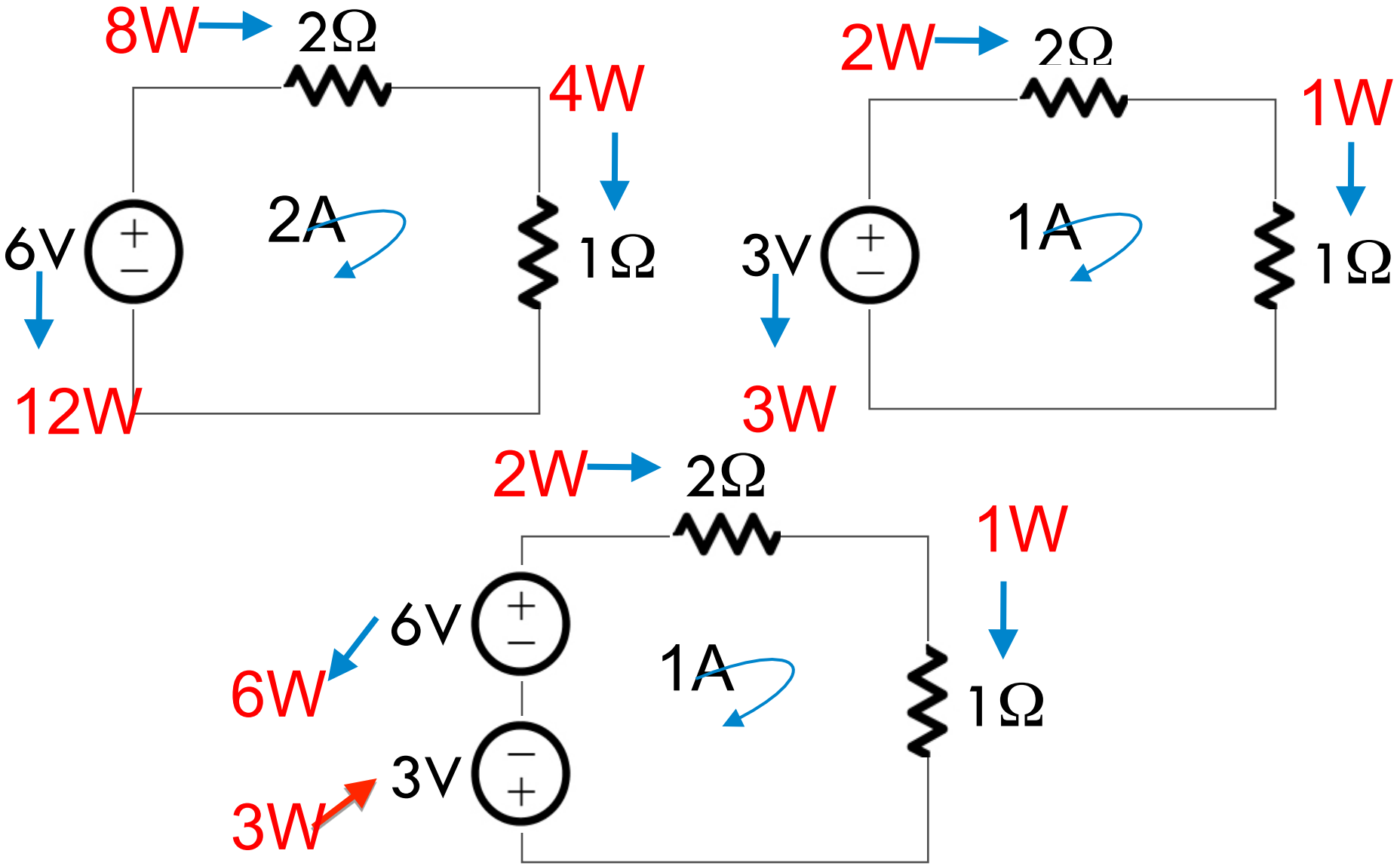
Case B

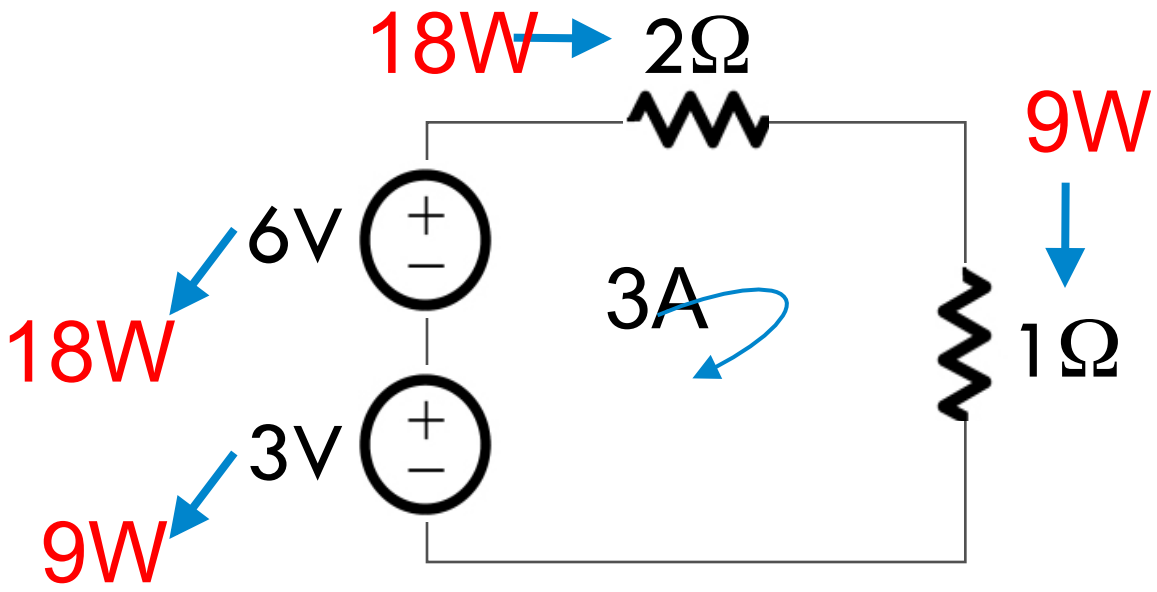


Superposition of Case A & B results in a NEW CASE C



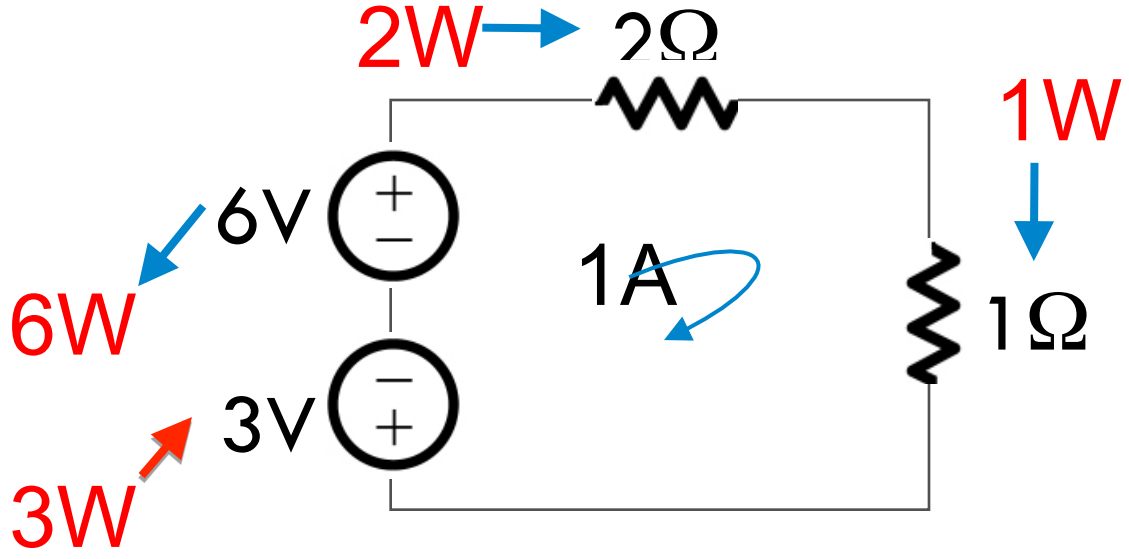
Superposition of Case A & B results in a NEW CASE D





The two cases are COMPLETELY Different

Superposition of POWER DOES NOT HOLD.



Superposition of voltages and currents are still valid

Therefore, the signal to noise ratio of $z(t)$ is

$$\gamma_z = M\frac{E[|s(t)|^2]}{\sigma_n^{\,2}}$$

If, instead of using the array of M elements, only the signal at a single array element, $u_o(t)$, is used, then

$$u_o(t) = s(t) + n(t) \tag{5.9}$$

The signal-to-noise ratio of $u_o(t)$ is

$$\gamma_u = \frac{E[|s(t)|^2]}{\sigma_n^{\,2}} \tag{5.10}$$

Comparing (5.8) and (5.10), we see that an M-element array can achieve an SNR improvement of

Spatial Processing Gain. ← $G = 10\log(M)$ dB (5.11)

in Additive White Gaussian Noise (AWGN) with no interference or multipath. This is the signal-to-noise ratio improvement provided by the array relative to the signal-to-noise ratio at a single element.